REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
21-03-2017	Final Technical Report	From 22-06-2015 To 22-12-2016

4. TITLE AND SUBTITLE
Fabrication Development and Flow Testing of Underwater Superhydrophobic Films for Drag Reduction

5a. CONTRACT NUMBER

5b. GRANT NUMBER
HR0011-15-2-0021

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Defense Advanced Research Program Agency
675 North Randolph Street
Arlington VA 22203-2114

10. SPONSOR/MONITOR'S ACRONYM(S)
DARPA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
DARPA expects the work performed under this Cooperative Agreement to be fundamental research, and it is, therefore, not subject to publication restrictions.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
By developing appropriate superhydrophobic (SHPo) films we have obtained a significant (> 20%) drag reduction for all flow conditions tested: in high speed water tunnel, in high speed tow tank, and with a motor boat on ocean water.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
				27	Kim, Chang-Jin
					19b. TELEPHONE NUMBER *(Include area code)* 310 825 0267

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Fabrication Development and Flow Testing of Underwater Superhydrophobic (SHPo) Films for Drag Reduction

Final Report
June. 23, 2015 – Dec. 22, 2016

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The Proposed

Task 1: Improve SHPo microstructures to enhance gas entrapment
1.1 Optimize trenches for maximum effective lifetime of trapped gas
1.2 Optimize trenches for stable gas replenishing mechanism
1.3 Develop self-regulated and self-powered gas replenishing mechanism

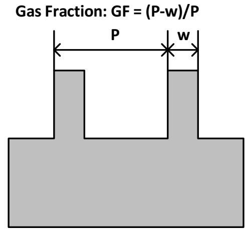
Task 2: Develop scalable fabrication of self-sustainable SHPo film
2.1 Develop whole-Teflon hot embossing for optimized passive surface
2.2 Develop whole-Teflon hot embossing for self-sustainable surface
2.3 Develop mechanized processing for scale-up manufacturing

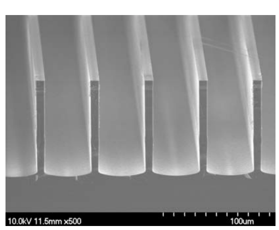
Task 3: Flow testing and characterization
3.1 Develop shear sensor for direct measurement of skin friction
3.2 Characterize developed surfaces using in-house water tunnel
3.3 Prepare surfaces and help testing them at DoD flow facilities
3.4 Develop and perform field tests in real marine conditions

Task 1: Improve SHPo microstructures to enhance gas entrapment

Task 1.1 Trench geometries to prolong gas trapping

Gas Fraction: GF = (P-w)/P





A typical silicon SHPo surface

- **Decide pitch *P* and gas fraction *GF* to use:**

Gas retaining ability $\propto 1/(P-w)$

Tradeoff

Drag reducing ability $\propto$ GF and P

Desired: small P with high GF

Our main choice: P = 50 μm and GF = 90%, considering theory and fabrication constraints

- Silicon SHPo surfaces are mostly used because the geometry can be precisely controlled.
- After molding is developed, Teflon SHPo films are also used to show scalability.

Task 1.1 completed.

Task 1.2 Trench geometries for stable gas replenishment

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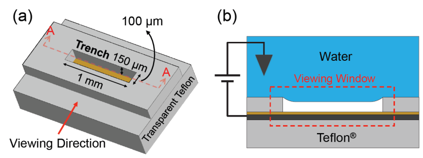
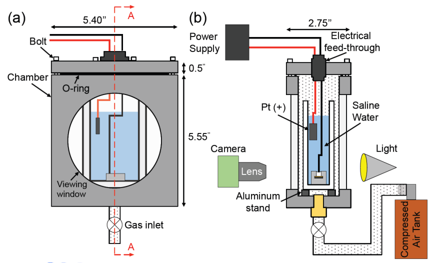
Visualization of gas replenishing process

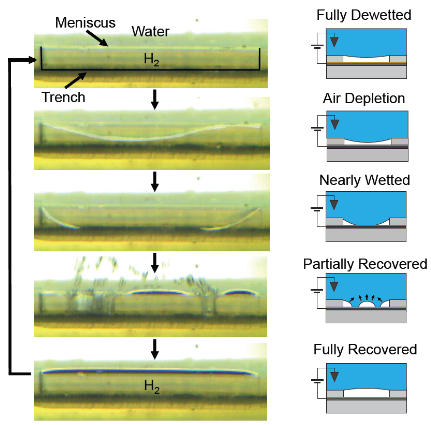
Sample and visualization direction:



High pressure chamber:



Gas recovery under 5 atm pressure:



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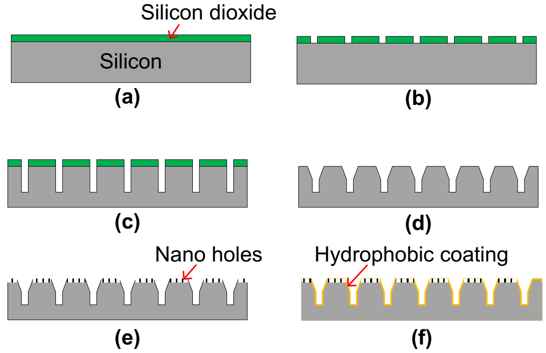
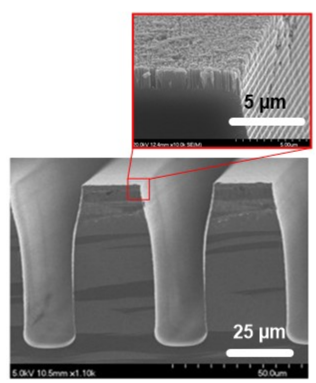
- SHPo surface whose trenches have SHPo bottom spreads gas much better
- We have developed fabrication process to obtain such a SHPo surface by changing the mold instead of adding more steps to the molding process





- The tapered sidewall greatly facilitated demolding
- The nanoholes on mold top creates “nanograss” at trench bottom, making it SHPo

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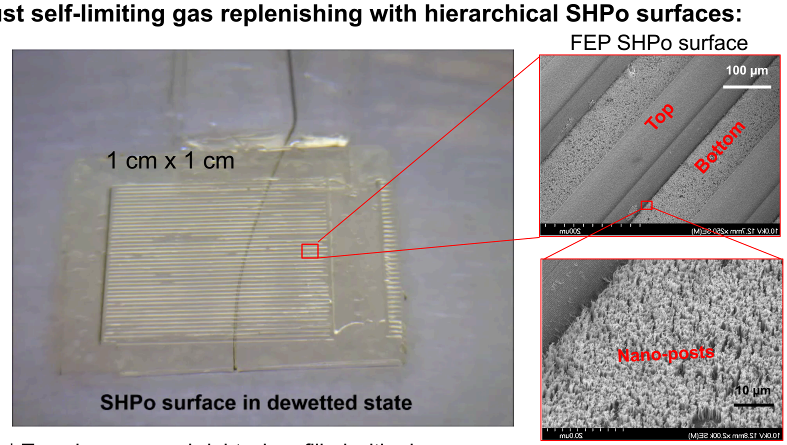
Robust self-limiting gas replenishing with hierarchical SHPo surfaces:

Video:



* Trenches appear bright when filled with air and dark when wetted by water

The bottom surface of the trenches desired to be SHPo for stable gas replenishment.

Task 1.2 completed.

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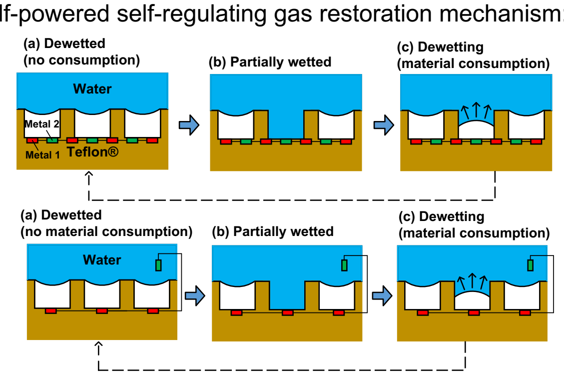
Task 1.3 Self-regulated and self-powered gas replenishing mechanism

Self-powered self-regulating gas restoration mechanism:



$$Cathode: 2H^{+} + 2e^{-} \Rightarrow H_2 \uparrow$$

$$Anode: M - e^{-} \Rightarrow M^{+}$$

- Self-powered electrochemical process
- Easy application w/o wiring

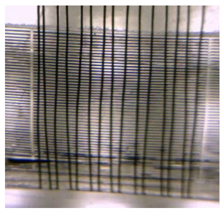
- The mechanism has been evaluated after developing fabrication process
- Differences and advantages have been studied and clarified.
- Choices of the material pairs have been investigated for performances.

The concept and fabrication verified with 1 cm x 1 cm sample

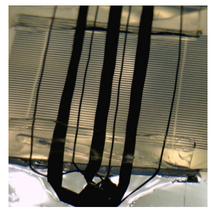
- No external power used
- When trenches are intentionally wetted, gas is generated
- When dewetted, gas generation stops, confirming the self-limiting ability

Vides played at 4x

Type I



5 mm



Type II

Self-regulated and -powered gas replenishment has been studied for its mechanism, material choices, and limitation and experimentally verified.

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Task 1.3 completed.

Task 2: Develop scalable fabrication of self-sustainable SHPo film

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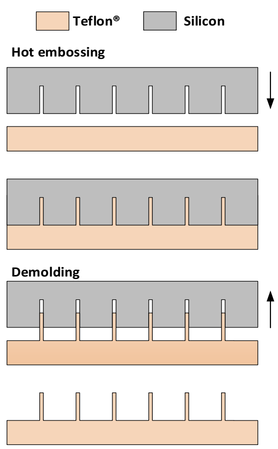
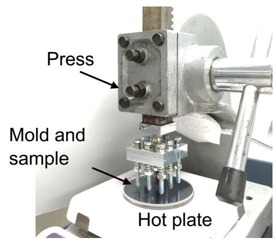
Task 2.1 Develop whole-Teflon hot embossing for passive SHPo surface

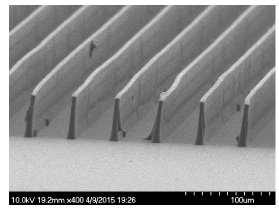
Overall processing sequence:





Hot embossing setup with manual press

P = 50 μm; GF = 90%



Typical result. Adequate for small samples (2 cm x 2 cm)

Numerous improvements and optimization made

- Temperature, heating time and ramping rate of hot plate, Si mold, and Teflon film
- Material type and thickness of Teflon film
- Custom-made press head for uniform pressure

Whole-Teflon hot embossing process to fabricate SHPo films verified.

Task 2.1 completed.

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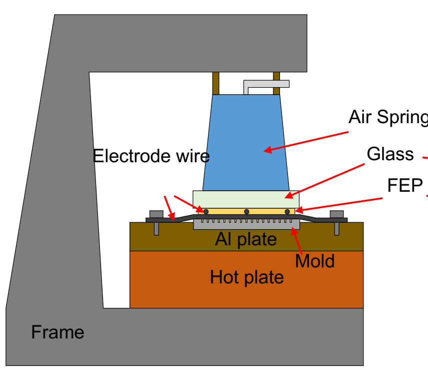
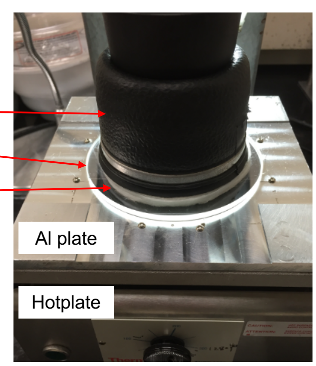
Task 2.2 Develop whole-Teflon® hot embossing for semi-active SHPo surface

Hot embossing setup showing the hot embossing of semi-active SHPo surface





- Air spring improved the pressure uniformity
- After hot embossing, aluminum (Al) plate would be removed from hot plate for fast cooling

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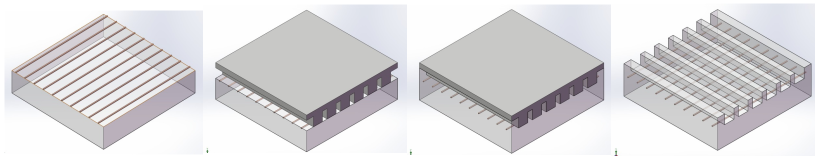
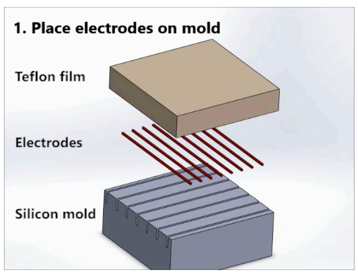
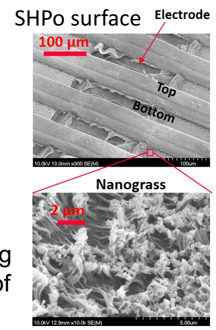
One-step hot embossing process proposed and developed.



Video: animation of the above process



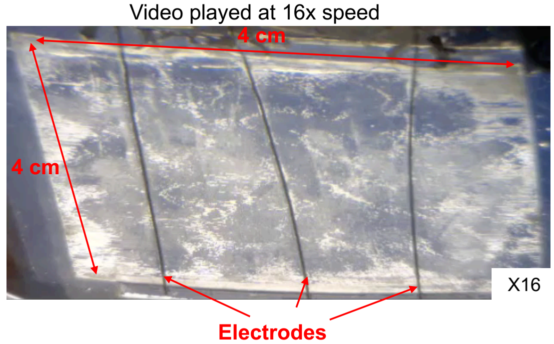
By making only the top of the silicon mold roughened, we succeeded to fabricate SHPo trenches with SHPo bottom surface, realizing the conclusion of Task 1.2.



We have successfully developed one-step hot embossing process for semi-active SHPo surface samples. However, it is limited to 2 cm x 2 cm samples if the trench bottom needs to have nanograss (found useful in Task 1.2). For SHPo films with smooth trench bottom, the current setup can fabricate 4 cm x 4 cm samples.

- Most of the area of the SHPo surface got dewetted (dark to bright color)
- This sample is large enough to fill the floating plate on some of the drag sensors in Task 3.1

Video played at 16x speed



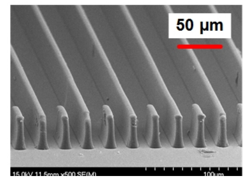
Whole Teflon hot embossing process developed for semi-active SHPo films.

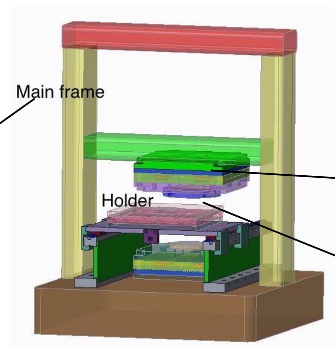
Task 2.2 completed.

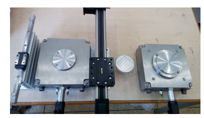
Task 2.3 Develop mechanized process for scale-up manufacturing

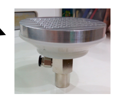
- Press frame custom-ordered to manufacture SHPo surface samples with a relatively large area (e.g., > 4 cm x 4 cm) with hot embossing.
- Note the improved quality of the microstructures compared with those in Task 2.1.
- The holder is computer-controlled to load, mold, demold, and release a Teflon film

Teflon® FEP









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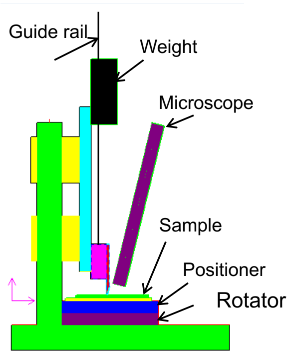
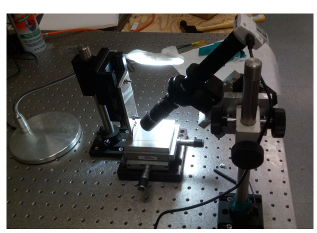
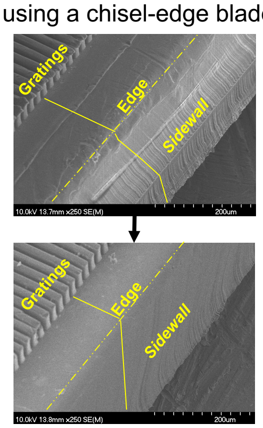
- Developed apparatus to cut whole Teflon samples
- Obtained well-defined edges with vertical sidewall, which minimize dead zone between SHPo samples
- Multiple samples can be tiled to form a large area





Sidewall improved by using a chisel-edge blade



Mechanized process to make whole Teflon films developed.

Task 2.3 completed.

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Task 3: Flow testing and characterization

Task 3.1 Develop shear sensor for direct measurement of skin friction

- In development stage, many different SHPo surfaces need to be evaluated
- Manufacturing of the many SHPo samples each in meters is unreasonable
- We hope to sense the drag of a surface sample ~5 cm in size (made from 4" wafer) placed on a desired location of the flow test without affecting the flow

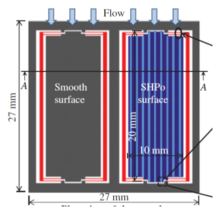
Common friction drag measurement methods:

	Methods	Pros	Cons
Indirect	Pressure drop	• Simple setup	• Only channel flow • Low accuracy
	Particle image velocimetry (PIV)	• TBL flow capability • Visualization of velocity profile	• Bulky and complex • Not for open water • Large uncertainty
Direct	Rheometer	• Simple setup • High accuracy	• Only Taylor-Couette flow
	MEMS floating element (optical)	• High accuracy • TBL flow capability	• Bulky optical setup • Fragile structure • Size limit • Fabrication challenge
	Pivot sensor (piezoelectric)	• High accuracy • TBL flow capability • Robust structure	• Assembly difficulty • Temperature& pressure sensitivity

Our previous MEMS shear stress sensor:

- Relative drag by two plates was proven useful
- MEMS fabrication: expensive but accurate
- Too fragile to attach&detach samples
- Reading with high-speed camera too bulky

Our previous MEMS shear sensor with double floating plates made of silicon



Park, Sun, Kim, *JFM*, (2014)

An ideal shear sensor would be:

- **Size range**: accept SHPo samples from 1 cm to 10 cm
- **Low profile**: fit into towing plate or ship hull
- **High resolution**: read with minimal floating plate displacement to reduce error
- **Robust**: functional in different environments
- **Sample attachment**: allow repeated sample attachment and detachment
- **Cost**: need to be economical for customization and mass manufacturing

Our approach

Low profile: keep the flexure design of MEMS sensor but use small encoder
Use a metal to provide the size range and allow sample attachment
A thin optical encoder may provide high resolution, robustness, and low profile

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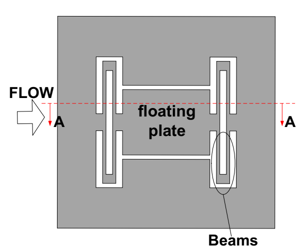
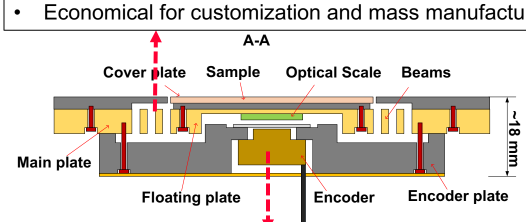
Goal: low-profile monolithic metal shear sensor with optical encoder

- Monolithic metal shear sensor requires machining extremely flexible (sub-millimeter wide and centimeters long) beams that suspend a floating plate.
- We have developed a new wire-EDM process to accomplish this goal.

- Metal beams that are narrow (0.25-0.5 mm) and long (50-100 mm) but thick (5-10 mm)
- Robust enough for sample change
- Economical for customization and mass manufacturing





Linear optical encoder:

- Resolution as high as 2 nm
- Robust against environmental parameter change
- Compact and low-profile: only ~18 mm thick

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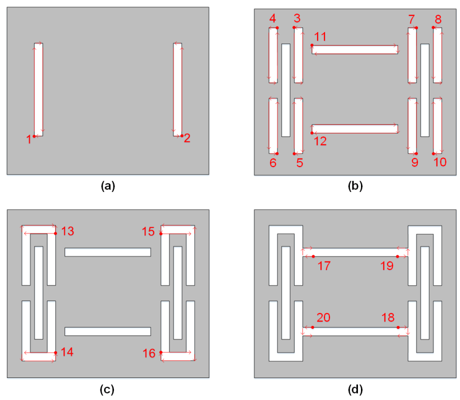
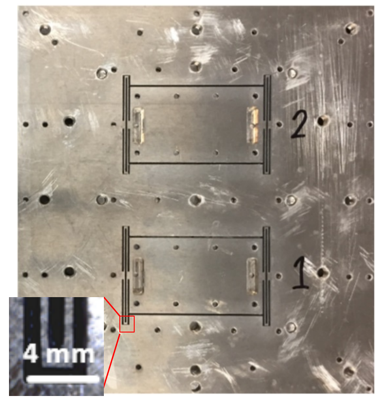
For floating plates, we have developed a new wire-EDM process:

- Special wire EDM process designed and proven using a commercial service (Wire Cut Company)
- Use of a right material and cutting sequence was the key to the success





Narrow (0.25-0.5 mm) and long (50-100 mm) beams carved out of a thick (5-10 mm) plate

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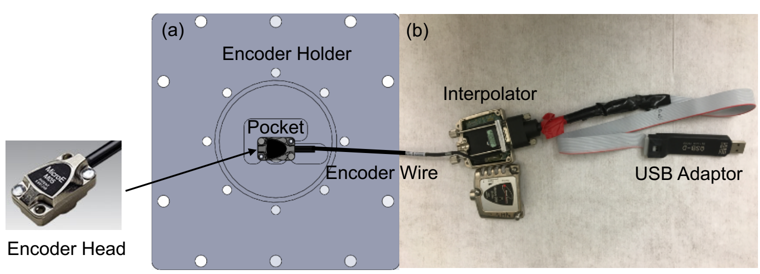
To read the floating plate displacement, we identified a small optical encoder

- Mercury 1000 model (resolution up to 78 nm) from Celera Motion
- Optical system of the shear sensor shown below
- One sensor system for each floating plate



(a) Bottom view of the encoder holder; the encoder head's laser is shining into the page. (b) Picture showing how the encoder is ultimately connected to the computer (USB).

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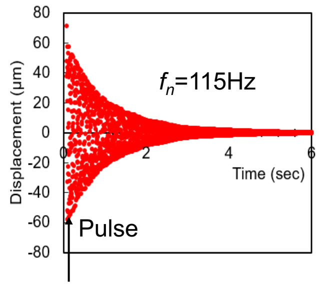
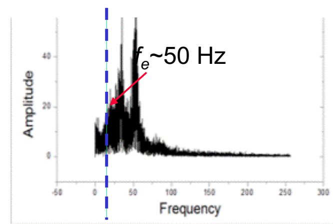
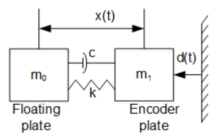
Structural characterization of the floating plate:

Natural frequency measurement

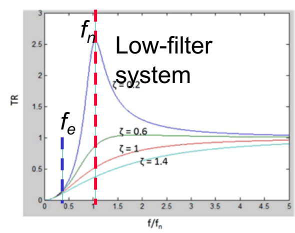


Noise frequency during testing





Transform function



Most of the noise (~90%) would be filtered

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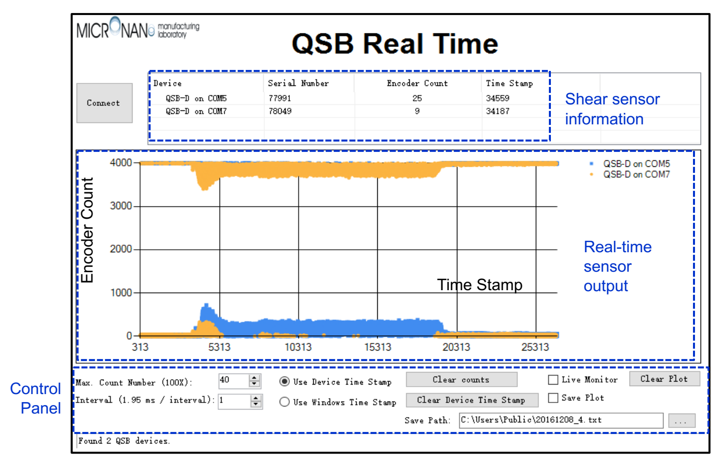
We have developed a software that displays the shear sensor output in real time, i.e., reading live drag reduction data during flow tests



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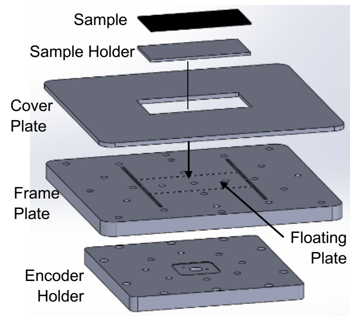
The shear sensing system

- Floating plate is carved out of the frame plate made of corrosion resistant aluminum (Al 5083 & Al 6061) or titanium (grade 2)
- Sample (SHPo or smooth film) is bonded on the sample holder, which is reversibly affixed on the floating plate
- Surfaces of sample and cover plate are flush
- Encoder is sealed in the encoder holder, which is affixed on bottom of the frame plate
- Newest design: a 4 cm x 7 cm sample displaces by 3-10 μm at Re = 1×10^6-1×10^7



Exploded view of the shear (drag) sensing unit (system)

The idea of metallic shear sensor verified and a low-profile system developed.

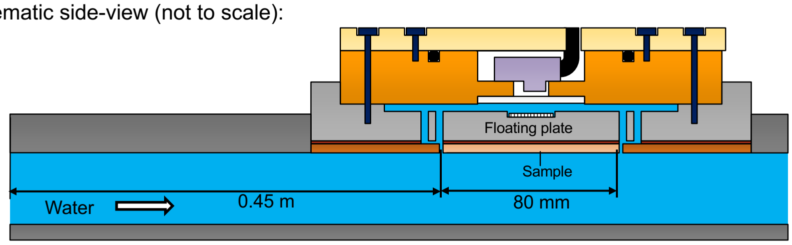
As its role has greatly expanded during our program, we have developed this sensor to a much more advanced level than originally planned. Recognizing its utility, we have filed a patent.

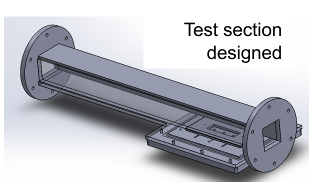
Task 3.1 completed.

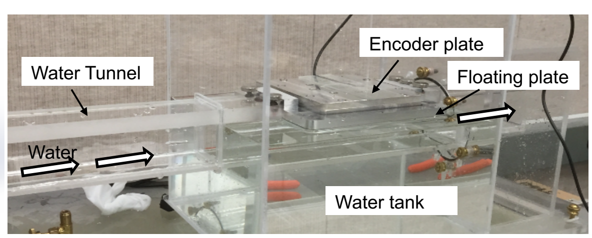
Task 3.2 Characterize developed surfaces using in-house water tunnel

The developed sensor verified using silicon passive SHPo surfaces

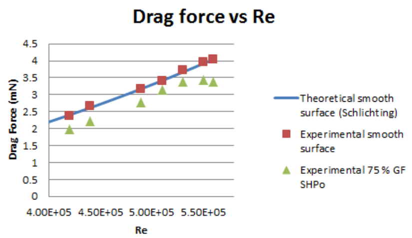
Schematic side-view (not to scale):

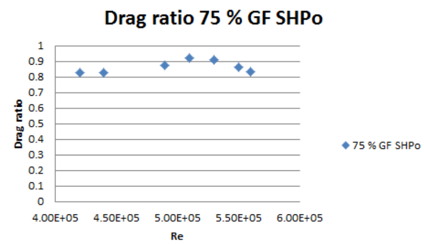






- The in-house water tunnel has been modified to accommodate the shear sensing unit. The test section of the in-house water tunnel was replaced to allow for testing of semi-active SHPo surfaces.
- Using passive a SHPo surface of P = 50 µm and GF = 75%, we have obtained drag ratio to smooth surface. It varied between 8% and 18%.



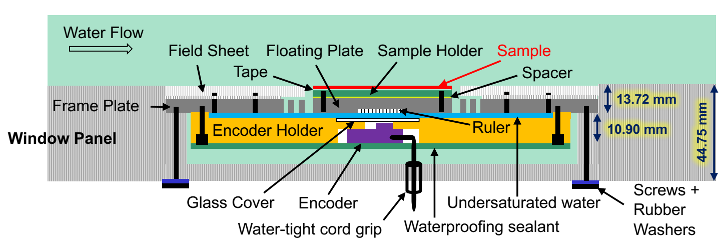


In-house water channel modified to accommodate 4 cm x 4 cm samples and confirmed to measure drag reduction

Task 3.2 completed.

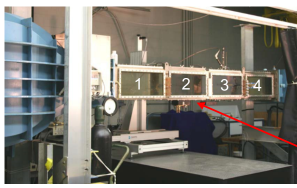
Task 3.3 Prepare surfaces and help testing them at DoD flow facilities

- Early on, it was decided we would perform the flow tests at NUWC water tunnel
- Developed a window panel with our drag sensing system to fit the water tunnel
- We have visited NUWC a total of 8 times to develop the tests and obtain data
- NUWC provided personnel and performed experiments with UCLA student
- The window panel has gone through several improvements and modifications. The latest is shown schematically below.

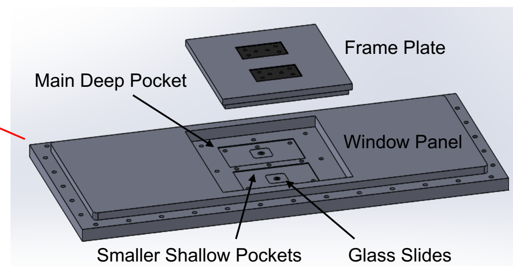


- The bottom window panel of test section 2 (or 3 for a few intermediate tests) was replaced with our window panel housing the drag sensing unit.
- The bottom position was chosen so that the testing window panel would hold the sample surfaces right-side up, avoiding any interaction with air bubbles floating along the top of the water tunnel.

NUWC water tunnel



Testing window panel



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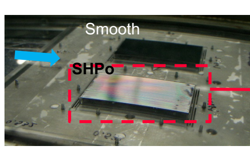
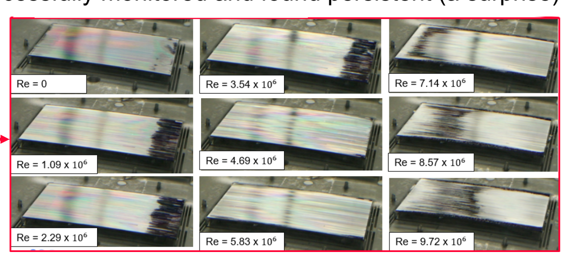
The 1st water tunnel experiment (December 15, 2015)

- Encountered gross water leakage
- Ran up to 2 m/s and confirmed the sensing accuracy when measured

The 2nd water tunnel experiment (March 10-11, 2016)

- Packaging modified to place the encoder outside water tunnel
- The state of plastron successfully monitored and found persistent (a surprise)





- Encountered water leakage at high flow speeds
- Drag data of smooth surface did not match theory well

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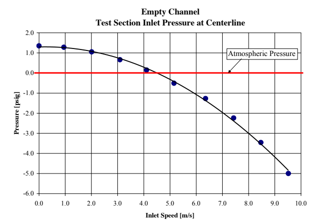
DARPA

The 3rd water tunnel experiment (June 13-15, 2016)

- All the problems encountered in the 2nd visit were fixed.
- Drag reduction was found enhanced as Re increased. This is the first experimental results showing the trend predicted by some numerical studies.
- Wetting dynamics of passive SHPo surfaces observed up to Re > 1.59×10^7
- At high speeds, the floating plate was found vibrating excessively and bumping into the surrounding frame.
- At high speeds, numerous bubbles were found accumulating underneath the floating plate, compromising the optical encoder reading and making the measurement unreliable at > ~5 m/s . We believe these bubbles were “generated” (not introduced from outside the tunnel) by the water pressure lower than the surrounding air at high speeds, as supported the NUWC data.



Hrubes and Henoch, Dec. 17, 2015

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DARPA

The 4th water tunnel experiment (Aug. 11, 2016)

- Tested high viscosity oil to prevent bubble accumulation and dampen excessive floating plate vibration. It slowed down but did not eliminate bubble accumulation, while causing many other problems. We decided not to use oil.

The 5th water tunnel experiment (Sep. 21, 2016)

- By placing the encoder inside the water tunnel (see the latest package), we successfully prevented excessive vibration. However, it made the sealing of the encoder more challenging.
- We filled the space between the floating plate and the encoder to with undersaturated water, preventing bubble generation in the space. The supersaturated water in the water tunnel is calculated to take hours to diffuse to the encoder region. This approach was found successful.
- We were able to collect data for three more (higher) speeds than ever before.
- Concluding all the major problems solved, we decided to make minor improvements in the next visit before starting full experiments.

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The test procedure are now established as follows.

1. Boil a full cooking pot of water on an induction heater
2. Cool the cooking pot in a tub of ice water until warm to the touch
3. Place the cooking pot full of cooled under-saturated water in the water tunnel
6. Put floating plate into the cooking pot at a slant (back side facing up at an angle)
7. Remove bubbles in the beams, screw holes, and near the ruler of the floating plate with a pipette
8. Put the encoder holder into the cooking pot at a slant (encoder lenses facing the rulers on the back of the floating plate)
9. Remove the bubbles in the screw holes and around the lip of the encoder holder with a pipette
10. Align the floating plate and encoder holes and screw together inside the cooking pot while still submerged underwater
11. Plug the holes meant for attaching the floating plate+encoder holder unit to the window with rubber plugs
12. Fill the water tunnel with water so that the cooking pot is submerged in water
13. Tilt the cooking pot enough so that the floating plate+encoder holder unit can be removed without exposing it to air (under-saturated water should be trapped in the gap)

The 6th water tunnel experiment (Oct. 27, 2016)

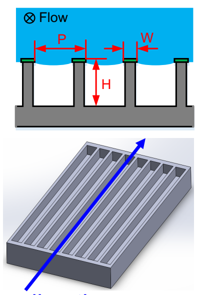
- Covering encoders completely with silicone sealant in holder prevented leaks
- Structural modifications made on floating plate and encoder holder did not prevent data shifts. We suspect the occasional bubbles passing the laser path. However, data can still be extracted before and after the shift.
- Two encoders used to allow a side-by-side collection of Smooth vs. SHPo data
- We have obtained drag data for all flow speeds. However, the data were irregular especially at low speeds. We concluded the SHPo surface was wetted while transferring the sample into the water tunnel in the undersaturated water.

The 7th water tunnel experiment (Nov. 17-18, 2016)

- Sample was kept flush with cover plate over time by making sample holder with aluminum (stronger threads), using one layer of tape (insoluble in water) for spacers, and using a metal feeler gauge
- Before data collection for each run, the water tunnel was run at Re= 1.45×10^7 for a 3-5 minutes to de-wet SHPo sample, but improvement was not noticeable.
- Bubble problem again, probably because of the higher speed than before.

The 8th water tunnel experiment (Dec. 13-16, 2016)

- Avoid the highest speed (Re = 1.62×10^7) and shorten the data collection time to reduce the bubble problem. This prevented the previous irregular data.
- Re-measured the spring constant of each floating plate as it drifted over time.
- Finally, we obtained full data, using the following 4 different SHPo samples.



Flow direction

GF = Gas fraction = (P-W)/P

Sample Name	Material	Pitch	GF	Height
Si (P50G90H50)	silicon	50 µm	90%	50 µm
Si (P50G90H30)	silicon	50 µm	90%	30 µm
Si (P25G90H30)	silicon	25 µm	90%	30 µm
FEP (P50G90H50)	Teflon	50 µm	90%	50 µm

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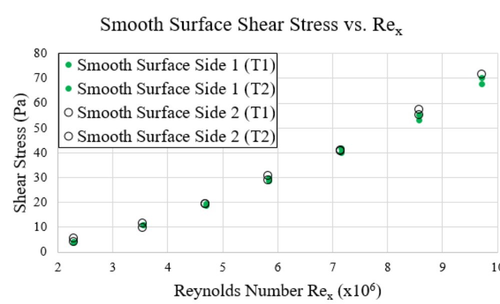
- For a baseline test, we tested two plates both with a smooth surface
- The results show very close displacement values over all speeds



- We can conclude that the two plates experience the same flow condition, supporting our double-plate approach that measures drag ratio of two different surfaces right next to each other.

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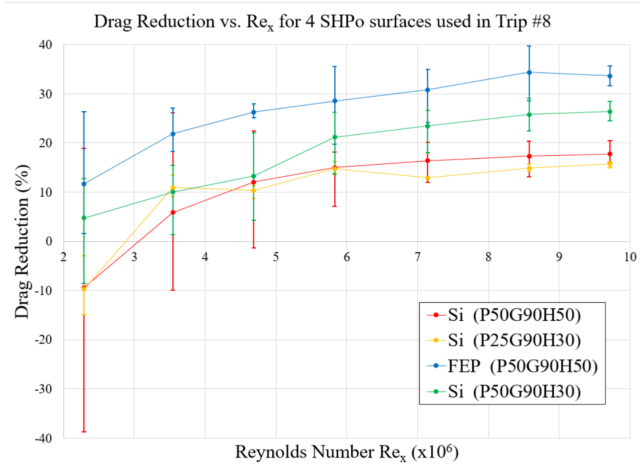
Results: Drag reduction of the 4 SHPo surfaces tested

Each error bar includes 3-5 data points



1. Drag reduction up to 34% (Re = 2.3 - 9.7x10^6) obtained in NUWC water tunnel
2. For a given SHPo surface, drag reduction increased with Reynolds number. This trend is the first experimental confirmation of some numerical predictions.
3. Si (P50G90H30) with 50 μm pitch produced larger drag reduction than Si (P25G90H30) with 25 μm pitch. This is the first confirmation in turbulent flows.
4. Si (P50G90H30) with 30 μm deep trench depth had larger drag reduction than Si (P50G90H50) with 50 μm deep trench. This trend may be because shallower trenches *start to* get wet later than deeper channels.
5. FEP (P50G90H50) had larger drag reduction than Si (P50G90H50). The whole Teflon surface of FEP (P50G90H50) may have retained thicker plastron than the Teflon-coated Si (P50G90H30), providing larger drag reduction.
6. Errors are apparent at slow speeds (Re = 2.3x10^6 and 3.5x10^6). This could be due to pre-wetting by the undersaturated water.
7. While 2 and 3 above are conclusive, 4 and 5 are somewhat speculative.

Task 3.3 completed.

Task 3.4 Develop and perform field tests in real marine conditions

1: Towing tank test at Stevens Institute of Technology

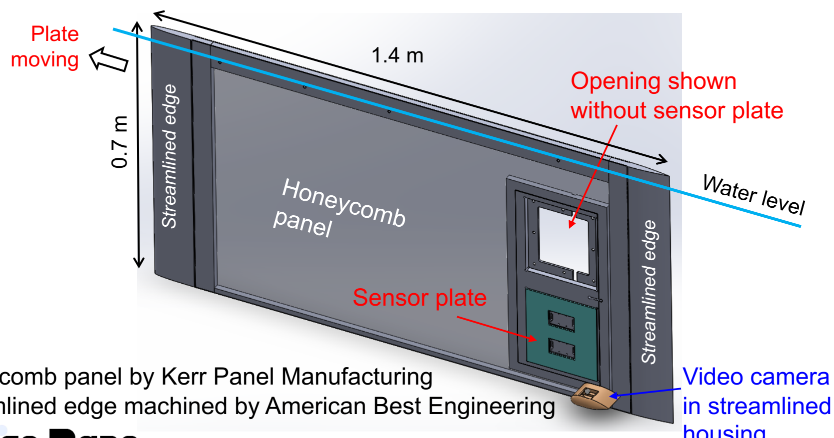
Motivation:
- Towing tank is the experimental facility that is most similar to real marine vessel (e.g., turbulent boundary layer flow, wave generation, etc.)
- Reynolds number and flow conditions could be well-controlled

Towing tank at Stevens Institute of Technology:
- 313 ft long and 16 ft wide, and can support water depths as high as 8 ft
- Speeds up to 100 ft/s with speed control of .01 ft/s

https://www.stevens.edu/research-entrepreneurship/research-centers-labs/davidson-laboratory/facilities-centers/design-evaluation

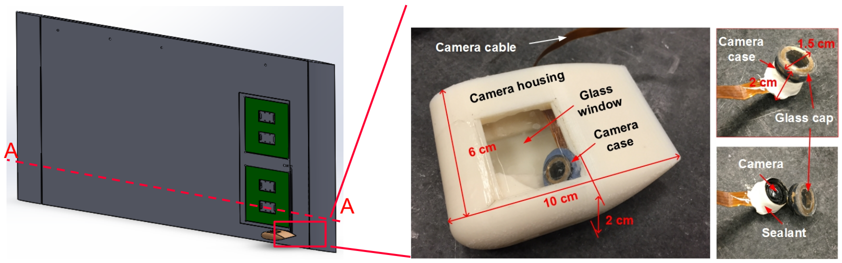
Attractive to our project:
- Open in air, this water does not lead to the false positive result (i.e., sustained plastron) obtained in the forced flows usually supersaturated with air.
- Our sensing plate avoids the main drawback of the towing tank test (i.e., drag affected by the attack angle of the towing plate).

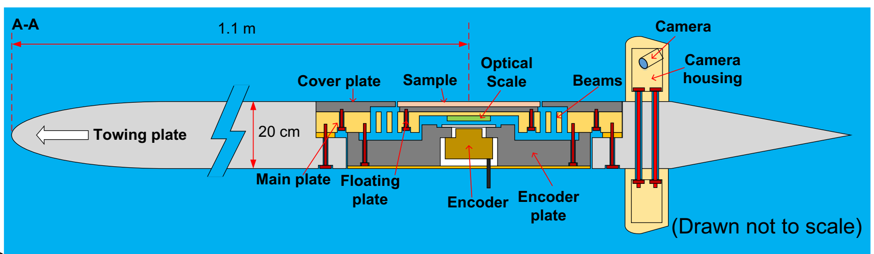
- We developed a towing plate using aluminum honeycomb panel with streamlined edges to reduce weight and splashing at high-speed flows, respectively.
- We developed an underwater camera system to observe SHPo surface during tests
- We visited them 3 times for tests: Nov. 1, Nov. 21-22, and Dec. 19-22, 2016



- Honeycomb panel by Kerr Panel Manufacturing
- Streamlined edge machined by American Best Engineering

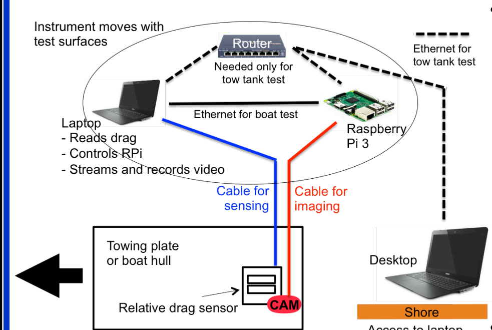
Shear sensor assembly and miniature underwater camera





Development of miniature underwater video camera system

- Monitoring the plastron during flow tests is critical to interpret the drag reduction data. For open water tests, the camera should travel with the surface under water.
- An undergrad student Ms. Jeong Lee (stipend by the NSF REU) has developed a miniature underwater camera system
- RaspberryPi 3 and its camera module adopted for their small size and low price



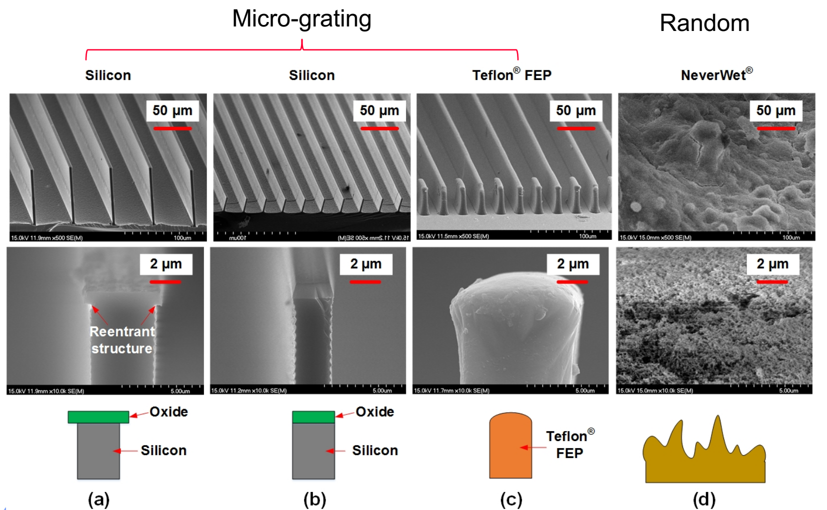
- The camera is placed inside a Nano Cache of Cachebox, whose cap is machined open and sealed with a glass piece for viewing. The twist-open cap allows adjustment of focus. We obtained an IP 48 level waterproof camera unit.

Camera unit
19 mm high
15 mm diameter

- During flow tests, a camera unit is placed in an streamlined housing (CAM)

DARPA

SHPo films fabricated and tested



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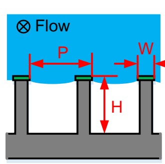
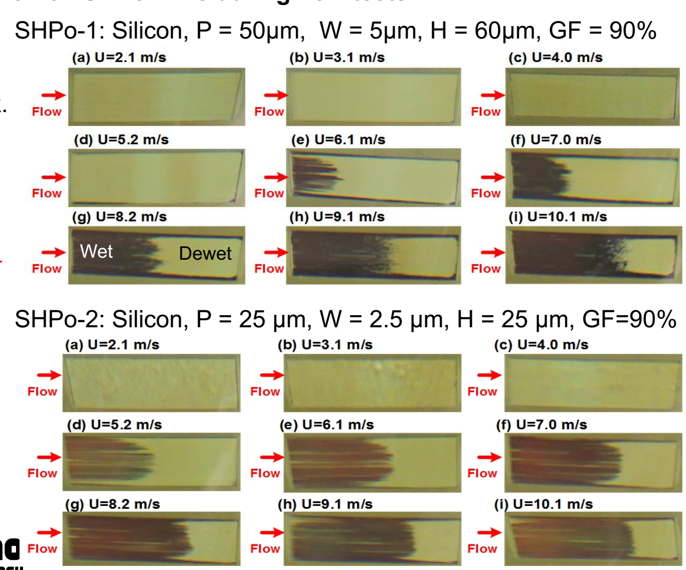
DARPA

The state of plastron on SHPo films during flow tests.

Wetted areas would appear dark.





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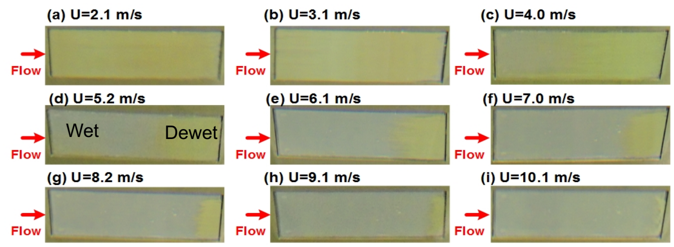
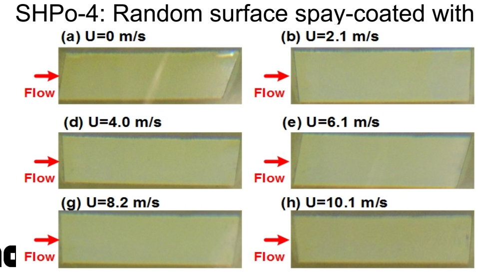
DARPA

SHPo-3: Teflon, P = 50 µm, W = 8 µm, H = 40 µm, GF = 90%



While all our SHPo surfaces were partially wetted at high speeds, NeverWet surface did not appear getting wetted.

SHPo-4: Random surface spay-coated with NeverWet®



Wetting not observed for NeverWet surface. The surface was dry when taken out of water

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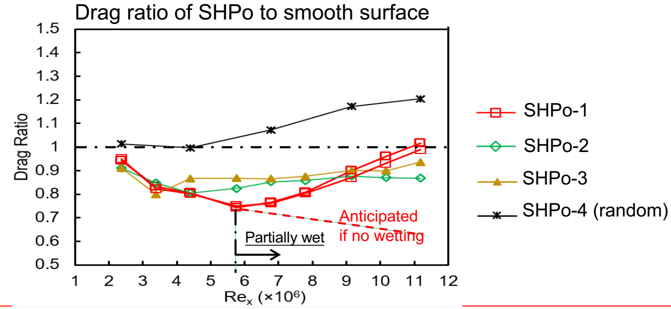
DARPA

Results:

- All our SHPo surfaces produced a drag reduction in tow tank tests
- We confirmed rough SHPo surfaces (used by most others) do not provide drag reduction in tow tank unless at very low speeds

Sample	Material	P (µm)	W (µm)	H (µm)	GF	Reentrant
SHPo-1	Si	50	5	60	90%	Yes
SHPo-2	Si	25	2.5	25	90%	No
SHPo-3	FEP	50	8	40	85%	No
SHPo-4	Random (NeverWet®)					



Drag reduction as much as 25% has bee obtained. This is the first report of successful SHPo drag reduction for high-speed tow tank tests.

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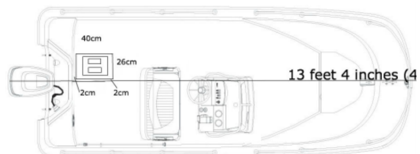
2: Boat test at Los Angeles coast

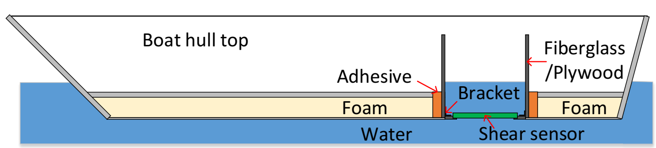


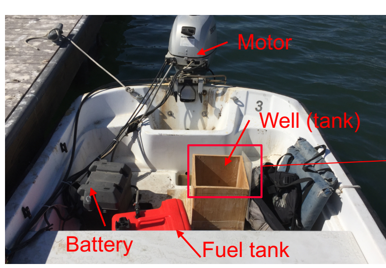
Motivation:
- Boat on seawater is a real application
- After the summer research by an undergrad Mr. Andrew Grabowski (funded by the NSF REU), we concluded a real boat is feasible
- Flow tests near UCLA would accelerate the research progress

The boat:
- 1979 13' Boston Whaler with 20 hp engine
- Safety: hull material of closed cells assures floatation at any adverse condition
- Purchased a used unit from the UCLA Aquatic Center at a discounted price
- It was deemed feasible to install our drag sensor through the boat hull

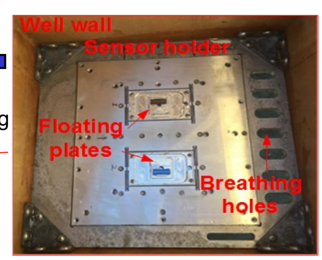
Marina del Rey, Los Angeles, California:
- Calm salt water environment in close proximity
- Easy access to ocean level turbulent conditions

- We have prepared an open tank inside the boat. Our senor plate is installed at the bottom of the tank so that its wet surface is flush with the hull surface. The onboard tank allows us to test multiple samples on one trip.





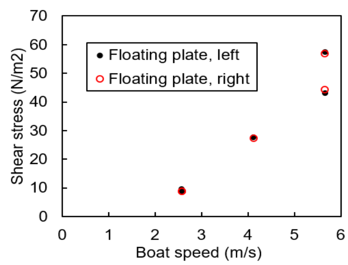
Boat moving

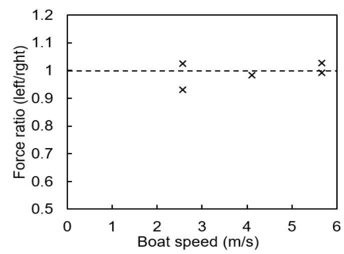


Shear sensor

Confirm the utility of the double floating plates approach

- Smooth surface samples were attached on both of the floating plates
- The trend of shear stress vs. speed showed uncertain flow condition
- Despite the uncertainties, the two smooth surfaces on the double floating plates always reported the same drag. If tested separately, a given surface would report different drag value each time at the same Reynolds number.





- The double floating plates ensure they experience the same flow conditions, so that the displacement difference is only by the sample surfaces on them. This approach is verified here for boat tests, too.

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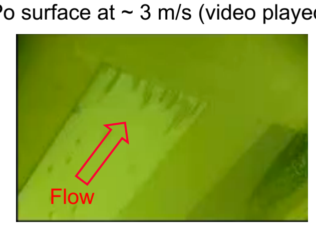
Results

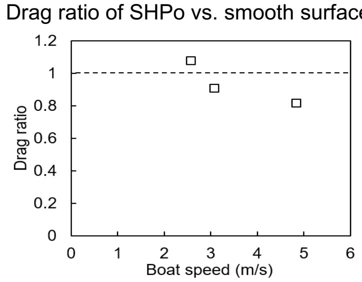
SHPo surface with P = 50 μm, W = 5 μm, H = 60 μm, and GF = 90%

SHPo surface at ~ 3 m/s (video played at x4)



- Bubbles initially trapped on surface
- Flows were found bubbly, keeping the passive SHPo surface dewetted

Drag ratio of SHPo vs. smooth surface



- Confirms Reynolds number effect

Drag reduction as much as 20% has bee obtained*. This is the first report of successful SHPo drag reduction for boat tests.

*After the project ended, now we are obtaining drag reduction over 30%

Task 3.4 completed.

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Summary

- The microstructure geometry for prolonged gas trapping has been designed for SHPo surfaces and implemented
- Molding process for whole-Teflon samples has been developed for passive and semi-active SHPo films
- Low-profile shear sensor with double floating plates has been developed to measure the drag ratio of SHPo-to-smooth surface accurately and conveniently under varying flow conditions
- SHPo surfaces were tested in high-speed water tunnel (NUWC) and produced drag reduction as large as 34%
- SHPo surfaces were tested in high-speed tow tank and produced drag reduction as large as 25%
- SHPo surfaces were tested under a motor boat on seawater and produced drag reduction as large as 20%
- <u>All the proposed tasks have been completed</u>

Discussions

- Our SHPo surfaces consist of parallel trenches with a high void fraction, unlike the random roughness most other groups use
- We were able to show how important the micro- and nano-scale details of the microstructures on the SHPo surfaces are for successful drag reduction
- The low-profile shear sensor developed is expected to be a major tool for experimental studies of skin friction drag in the future
- While obtaining drag reductions up to 34% in a high-speed water tunnel, we have found why it misrepresents the flow condition of boats. This explains why the success with water tunnel has never been duplicated in open water
- Our successful drag reduction in high-speed tow tank is the first ever reported
- Our drag reduction in high-speed boat is the first ever reported
- Surprisingly, the semi-active SHPo surface was not needed for the boat tests. While very sencouraging for applications, it did not give us the chance to study the semi-active SHPo surfaces as much as we had planned.